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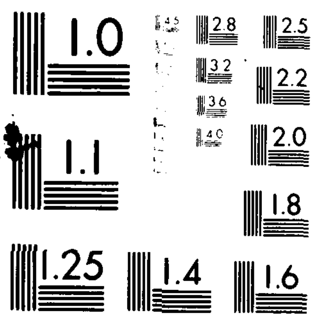

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Technical Report

HUMAN ENGINEERING GUIDES TO DESIGN OF DISPLAYS FOR UNDERWATER APPLICATIONS

W. S. Vaughan, Jr.
Oceanautics, Inc.

J. A. S. Kinney
Naval Submarine Medical Research Laboratory

Contract Number: N00014-79-C-0602
Work Unit Number: NR 196-157

Prepared for:

Engineering Psychology Programs
Psychological Sciences Division
Office of Naval Research
Arlington, Virginia 22217

Prepared by:

OCEANAUTICS, Inc.

422 Sixth Street
Annapolis, Maryland 21403

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This report contains recommendations for designers of displays for systems that operate underwater. The recommendations are based on a foundation of research and analyses contained in a companion document (Vaughan and Kinney, 1980). Both the current report and the database document are organized by designer decisions related to the legibility of panel displays and to the visibility of painted objects. Five decisions comprise the content organization

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of the report: eye-to-console distance, symbol size, display luminance, peripheral location, and use of color. Material presented within each section serves first, to provide a rationalè for the significance of human factor considerations to the decision; second, to provide necessary translations of scientific concepts into engineering concepts; third, to state concise recommendations for how to resolve the design issue from the viewpoint of human factors.

Principal criteria for the organization, content and format of this guidebook were to make human factors information available to engineer-trained designers so as to be easily accessible, easily assimilated and directly usable.

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Several engineers who design displays for underwater systems reviewed earlier drafts of the guidebook and their suggestions modified the final product toward a more usable handbook. We particularly thank Mr. Joe Allulis of Naval Surface Weapons Center, Mr. George Austin, Mr. Sid Brickerd and Mr. John Quirk of Naval Coastal Systems Center and Mr. Ed Spencer of Naval Facilities Engineering Command for arranging our access to professional designers.

We are especially indebted to Mr. Art Shipley of the Naval Surface Weapons Center for helping us acquire some understanding of the general procedure by which engineers design underwater systems, and more importantly, what they think about when they are designing.

Mrs. Anne S. Mavor helped conduct interviews with design engineers and helped model the design process as a frame for organizing the guidebook.

HUMAN ENGINEERING GUIDES TO DESIGN OF DISPLAYS FOR UNDERWATER APPLICATIONS

I. INTRODUCTION

This report is intended for use by design engineers as a human factors guide to display component selection for underwater systems. Main applications of the guides are to vehicle and work station console displays, displays for diver-worn and hand-held equipments, and to painting underwater floats and structures. The material is organized by design decisions at that stage of the design process where sensory and perceptual characteristics of observers need to be accounted for in order to make displays legible and painted objects visible in a range of underwater viewing environments. The guides do not address those issues of display design that concern cognitive compatibility; i.e., how to make a display communicate easily to a user, fit his way of thinking so as to be readily assimilated. Solutions to these issues are probably no different underwater than they are in air applications. The issues of legibility and visibility, however, are more complex problems in underwater viewing environments due to the effects of turbid water and vision through a faceplate.

The format and content of the guide book are intended to reduce clutter, and to focus the designer's attention on the direct impact of human factor considerations in specific design decisions. The content is solution-oriented; recommendations are given as succinctly and clearly as possible without elaborate documentation or qualification. A companion report (Vaughan and Kinney, 1980) serves as a database of scientific results and analyses from which recommendations in this report have been derived. A designer who wishes to explore the in-depth foundations of the recommendations can easily access that material since the two documents, the 1980 database report and the present designer guide, have a common content organization.

Other measures have been taken to help insure the easy use of the guidebook by designers. Early work on the problem of low utility of human factors handbooks (Meister and Farr, 1966; Meister and Sullivan, 1967; Meister and Farr, 1967) analyzed reasons why engineers tend not to use human factors guidebooks. In general, previous handbooks have been compilations of research results on basic human processes or capabilities and have been more useful to other scientists than to designers. Meister and Farr, 1967, made several suggestions for how to design a handbook for acceptance by engineer-trained designers, and these have been used as criteria for the format and content of the current guidebook. Guidebook design criteria include the following features:

- Focus on providing specific answers to specific display design issues.
- Access material by specific design decision.
- Present recommended solutions to design problems based on available human factors information.
- Help the designer comprehend the significance of the human factor issues related to the design decision.
- Use graphs and tables and pictures rather than words.
- Translate scientific jargon into concepts and measures familiar to engineers.

Meister, D., and Farr, D. E. The utilization of human factors information by designers. Canoga Park, Calif.: System Effectiveness Laboratory, The Bunker-Ramo Corporation, 1966.

Meister, D., and Farr, D. E. The utilization of human factors information by designers. Human Factors, 1967, 9(1), 71-87.

Meister, D., and Sullivan, D. J. A further study of the use of human factors information by designers. Canoga Park, Calif.: The Bunker-Ramo Corporation, 1967.

Vaughan, W. S., Jr., and Kinney, J. A. S. Vision-perception research and analyses relevant to display design for underwater applications. Annapolis, Md.: Oceanautics, Inc., 1980.

II. HUMAN ENGINEERING GUIDES

A. Eye-to-Console Distance

1. Problem Analysis

Seating arrangements and display console placements in aircraft and other vehicle systems that operate in air environments are designed for a 28-30 inch (71-76 cm) eye-to-console distance. This distance enables an operator with shorter than normal length arms to reach panel controls.

In underwater applications, a 28-30 inch viewing distance is too long; many displays cannot be made bright enough to penetrate this distance of turbid water. Seating and console arrangements should enable the operator to be very close to his displays; particularly in turbid water environments such as harbors, rivers and bays.

Instead of arm length, the determining human factor in design for eye-to-console distance is accommodation: the ability of the eyes to focus at close range, and to hold this focus for several hours without experiencing eye fatigue. Accommodative capability is a function of age; younger eyes can focus very close objects, older eyes focus at progressively longer distances.

Eye fatigue during sustained, close-in visual work is difficult to demonstrate or measure. However, to guard against the possibility of eye fatigue an accepted rule of thumb is to design so that the observer uses no more than half of his accommodative capability.

2. Translation Aids

Accommodation is measured as that distance away from the eyes where a visual stimulus shifts from blurred to clear. This measure is called the near point of accommodation.

Accommodative capability is usually expressed as an index in units derived from the near point measure. The index is called

diopters of accommodation. A diopter is the reciprocal of the near point in meters, i.e.,

$$D = \frac{1}{\text{Near point (m)}}$$

In order to apply the rule of thumb for fatigue-free, close-in visual work the following formula is used:

$$\text{Minimum Viewing Distance (m)} = \frac{1}{.5D}$$

or

$$\text{Minimum Viewing Distance (m)} = \text{Measured Near Point} \times 2$$

Table A.1 shows the average near point of accommodation and the minimum viewing distances for fatigue-free, close-in visual work for persons of different ages. Figure A.1 illustrates these limits.

3. Recommendations

Design the seating and display console arrangements so the diver can be comfortable and close to the displays for legibility in turbid water. A design that provides a range of eye-to-console distances between 10 and 20 inches will support long-duration, fatigue-free display monitoring by operators in the age range of 25 to 40 years.

Table A.1. Limits to Fatigue-Free, Sustained Visual Monitoring

Age	Accommodation Near-Point (m)	Diopters 1/Near-Point (m)	.5D	Rule of Thumb for Sustained Close-In Visual Work: Distance (m) $= \frac{1}{.5D}$
40	.25	4.0	2.0	.50 m
35	.18	5.6	2.8	.35 m
30	.14	7.0	3.5	.30 m
25	.12	8.5	4.25	.25 m
20	.10	10.0	5.0	.20 m

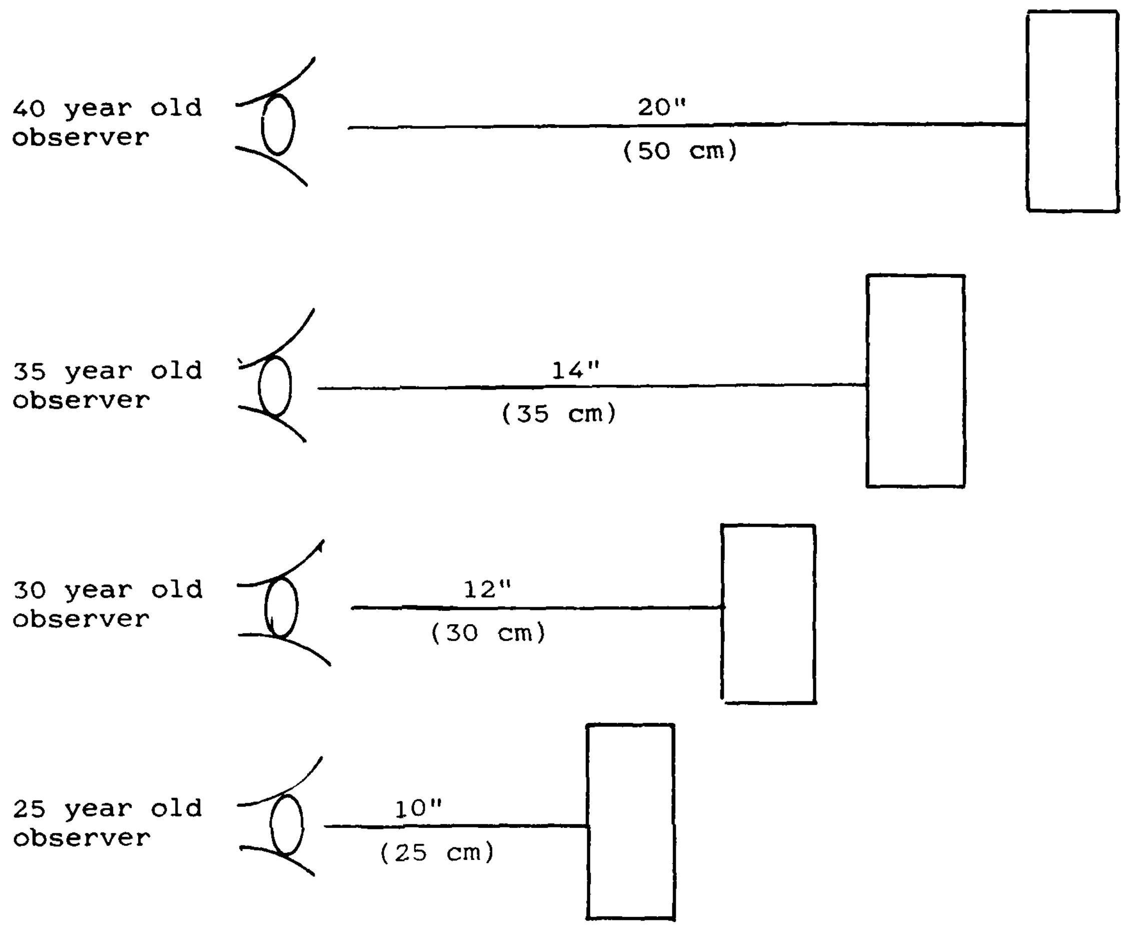


Figure A.1. Limits to Close-In, Fatigue-Free Display Monitoring

In turbid water, diver will need to be close to the display in order to read it. Design tne seating and console arrangement so that diver can view displays comfortably with between 10 and 20 inches of eye-to-console distance depending on the age of the observer. An eye-to-console distance of 14 inches is recommended as an optimum.

B. Symbol Size

1. Problem Analysis

To a display manufacturer or designer, size is character height and width; but to the human visual-perceptual system size is visual angle, i.e., the size of the image being projected to the diver's eyes. Therefore, viewing distance and character dimension must be considered simultaneously in order to determine the effective perceptual size of alternative alpha numeric symbols. As a symbol of any given height and width dimensions is moved closer to the eye, its visual angle and, therefore, its perceived size increases.

In traditional applications, acceptable symbol size ranges between 10 and 20 minutes of arc, i.e., visual angle. The smaller displays are acceptable under conditions of high luminance; the larger displays are more appropriate for low levels of luminance. This is because luminance and size combine to affect legibility; within limits, equivalent legibility can be achieved by using higher luminance with small displays, lower luminance with large displays.

The size vs luminance interaction is particularly important for achieving a uniformly bright set of readouts on a console for underwater applications. Smaller displays need to be of higher luminance than larger displays in order to appear equally bright.

Self-luminous alpha numeric symbols need to be larger and/or more luminous for legibility underwater as compared to air viewing environments. This is mainly because of the differences in contrast. Most bodies of water are turbid to some degree and the suspended particles scatter light away from the eye, reducing luminance contrast between the display and its background.

2. Translation Aids

Manufacturers' catalogues describe display size by character height and width. The 'size' that affects legibility, however, is visual angle, the size of the image at the eye expressed in units of degrees and minutes of arc.

Visual angle is a function of the symbol size and its viewing distance. It can be computed by a formula applicable to the small angles characteristic of displays on hand-held equipment and on vehicle consoles. Character height is the dimension typically used to defined symbol size in the formula as follows:

$$\theta' = \frac{(57.3)(60)(h)}{d}$$

where

θ' is visual angle in minutes,

h is character of digit height, and

d is viewing distance, where $\underline{h}$ and $\underline{d}$ are in common units.

Figure B-1 provides a rough guide to digit size and viewing distance combinations that yield 'small' (20 minutes of arc), 'medium' (40 minutes of arc), and 'large' (80 minutes of arc) visual angles as applied to symbol legibility underwater. The figure shows that at a typical viewing distance of 14 inches, an .08 inch-high digit will appear 'small', a .16 inch-high digit will appear 'medium', and a .32 inch-high digit, 'large' in size.

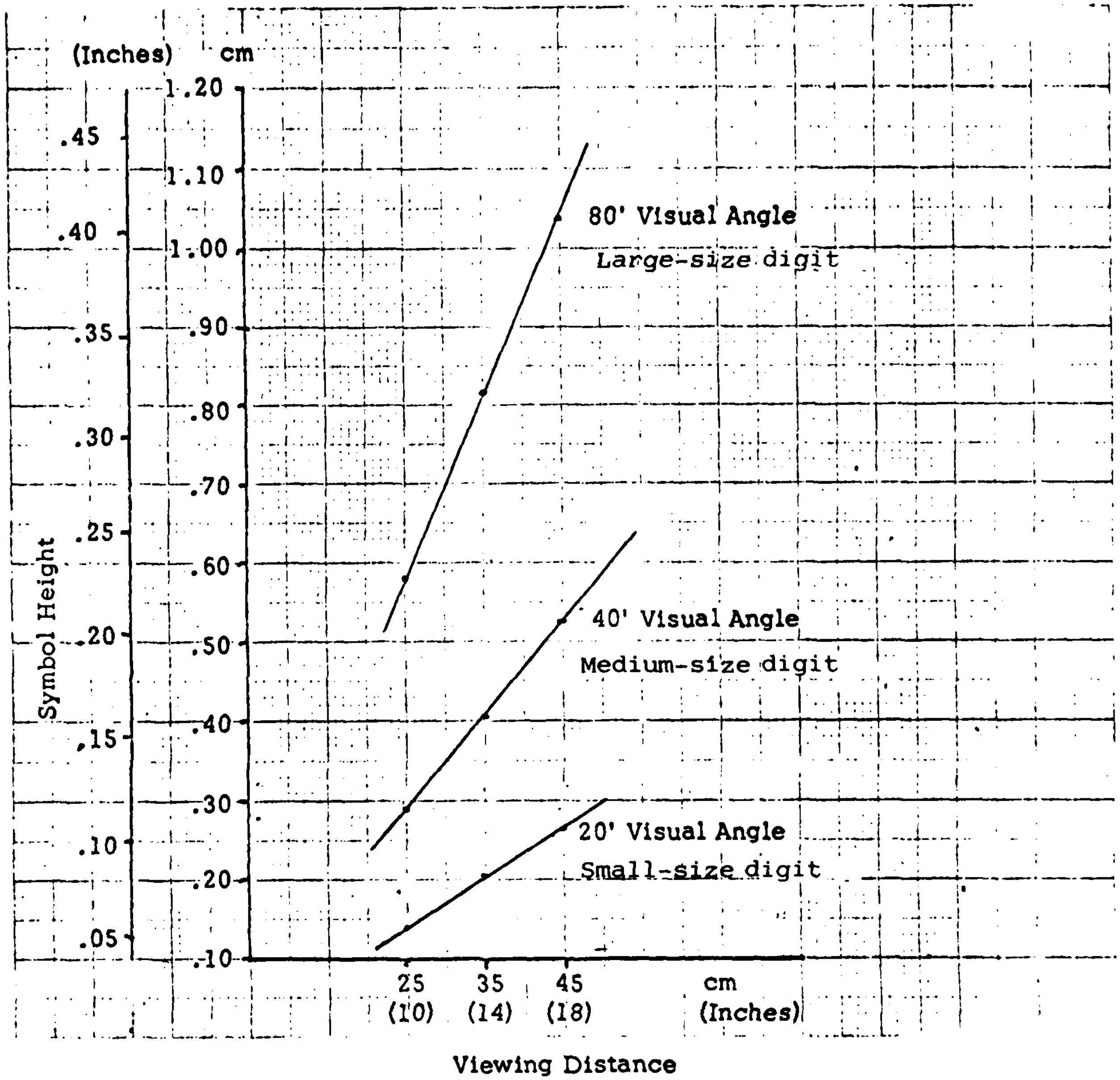


Figure B-1. Combinations of Symbol Height and Viewing Distance Which Yield Small, Medium and Large Visual Angles

3. Recommendations

- Use alpha numeric symbols of a height whose visual angle lies between 40 and 80 minutes of arc. Use Figure B-1 (pg. 8) as a guide to character heights and viewing distances which combine to yield visual angles in this range.

- Assuming a viewing distance of 14 inches, the recommended character height is in the range .16 - .32 inch. Extending the viewing distance to 18 inches expands the recommended range to .20 - .40-inch character height.

- Do not use characters whose visual angle is larger than 80 minutes of arc since the improvement in legibility will be marginal and console space needs to be conserved. A character height of .50-inch is probably the largest symbol you will need to consider.

- Do not use characters whose visual angle is less than 40 minutes of arc unless the application is restricted to clear water only; i.e., open or coastal oceans. For these waters use character sizes in the range 20-40 minutes visual angle.

- In the size range 40-80 minutes visual angle, displays of approximately equal luminance will appear equally bright. If the panel includes symbols of disparate sizes: i.e., some 20 and some 80 minutes visual angle, the smaller units must be of higher luminance than the larger units in order to appear equally bright.

- In general, display legibility in underwater environments is more effectively accomplished by increasing luminance than by increasing size.

C. Display Luminance

1. Problem Analysis

How much luminance is required of a self-luminous or transilluminated display in order for the diver to see it clearly? The answer depends on five factors:

- Ambient luminance: Is the water dark or illuminated? In the dark, display luminance is the determinant of legibility; in illuminated water, luminance contrast between the display and the background is the determinant.
- Turbidity of the water: Particles suspended in the water reduce the amount of energy transmitted from the source to the eye.
- Viewing distance: The farther the light has to travel, the less energy from the source arrives at the eye. This factor combines with turbidity effects to reduce light energy as it travels through the water.
- Display size: Dimensions of the display element combined with viewing distance define a visual angle. Displays of large visual angles are more easily seen (i.e., require less luminance for legibility) than displays of small visual angle.
- Display color: Depending on the turbidity of the water, the amount of light energy transmitted along a pathway will be a function of its wavelength or color.

Requirements for at-the-source display luminance increase as the level of ambient luminance increases, as the water turbidity increases, as the eye-to-display distance increases and as the visual angle 'size' of the display decreases.

2. Translation Aids

Display manufacturers' catalogues describe the 'intensity' of their displays in a variety of units: foot Lamberts (ft-L), millilamberts (mL), candelas per square meter (cd/m^2) are used to describe most incandescent filament and fiber optic displays; millicandelas (mcd) and microcandelas (μcd) are reported for LED displays; and mean spherical candle power (mscp) is used to describe small-diameter lamps. Some of these measures are units of intensity; others are of luminance. If the designer is looking for the 'brightest' display element from a set of alternatives, he first has to translate the different units to a common base. The general measure appropriate to human vision is luminance and the preferred unit of luminance is candelas per square meter (cd/m^2). Other units can be translated into cd/m^2 by the following procedures and formulas.

a. Foot Lamberts (ft-L)

Multiply ft-L by 3.426

$$cd/m^2 = 3.426 \text{ ft-L}$$

b. Millilamberts (mL)

Multiply mL by 3.183

$$cd/m^2 = 3.183 \text{ mL}$$

c. Millicandelas (mcd)

Multiply mcd by 10^3 and then divide by 'apparent emitting area'* in mm^2.

$$cd/m^2 = \frac{\text{mcd } (10^3)}{mm^2 \text{ emitting area}}$$

*'Apparent emitting area' may be a catalogued characteristic of LEDs; otherwise designer will need to approximate dimensions of the emitting area.

d. Microcandelas (μcd)

Divide μcd by apparent emitting area in mm^2.

$$cd/m^2 = \frac{\mu cd}{mm^2 \text{ emitting area}}$$

e. Mean Spherical Candle Power (mscp)

Multiply mscp by 10^6 and then divide by πr^2 where $\pi = 3.1416$ and r is the radius of the lamp in millimeters.

$$cd/m^2 = \frac{mscp\ (10^6)}{\pi r^2}$$

3. Recommendations

- In dark Oceanic, Coastal or Bay water applications, provide for an adjustable display luminance in the range 0.5 to 20.0 cd/m^2. This assumes a display of any color whose size is between 20' and 80' visual angle and which is to be viewed at a distance of 18 inches or less. Table C.1 (p. 14) shows specific values of display luminance required for clear legibility under a variety of conditions; note that all are within 20 cd/m^2. Also, levels of luminance adequate for an 18-inch viewing distance are adequate for closer distances.

- In dark Harbor water, provide for display luminance as shown in Table C.2 (p. 15) for the combination of size, color and viewing distance of the design application. Note the advantage of Red light in Harbor Water.

- In illuminated waters, where luminance contrast determines legibility use Table C.3 (p. 16) as a guide. The general rule is that luminance at the eye should have a contrast ratio of .40 with ambient luminance at low light levels, and .20 at high light levels.

Formula for contrast ratio is as follows:

$$\text{Contrast Ratio} = \frac{\text{Display Luminance} - \text{Background Luminance}}{\text{Background Luminance}}$$

or

$$CR = \frac{DL}{BL} - 1$$

If ambient luminance is not measurable use Table C.4 (p. 17) as a guide.

- In harbor waters at shallow depths during sunlight conditions, source luminance requirements are very high and beyond the capability of technologies such as LED displays.

Table C.1. Display Luminance (cd/m^2) Required for Clear Legibility in Dark Oceanic and Bay Waters At 45 cm (18 Inches) Viewing Distance

Water Type	Display Color and Size (Visual Angle)								
	Green Display			White Display			Red Display		
	20'	40'	80'	20'	40'	80'	20'	40'	80'
Clear Ocean	3.4	1.5	.5	3.4	1.5	.5	3.8	1.6	.6
Coastal Ocean	5.2	2.2	.8	5.2	2.2	.8	6.6	2.8	1.0
Bay	16.5	7.0	2.5	10.3	4.4	1.6	8.3	3.5	1.3

Table C.2. Display Luminance (cd/m^2) Required for Clear Legibility in Dark Harbor Water

Display Size in Visual Angle	Display Color and Viewing Distance								
	Green Display			White Display			Red Display		
	10 In.	14 In.	18 In.	10 In.	14 In.	18 In.	10 In.	14 In.	18 In.
20'	330	1,650	11,000	165	825	4,714	83	660	3,300
30'	200	1,000	6,667	100	500	2,857	50	400	2,000
40'	140	700	4,667	70	350	2,000	35	280	1,400
50'	100	500	3,334	50	250	1,430	25	200	1,000
60'	70	350	2,334	35	175	1,000	18	140	700
70'	60	300	2,000	30	150	857	15	120	600
80'	50	250	1,667	25	125	715	13	100	500

Table C.3. Amounts of Luminance (cd/m^2) Required for Clear Legibility in Illuminated Water

Ambient Water Luminance	Luminance Required At the Eye for Clear Legibility	Luminance Required At the Display Source for White Light At 14 Inches Viewing Distance			
		Open Ocean	Coastal Ocean	Bay	Harbor
3.4 cd/m^2	5	5.2	7.1	12.0	1,250
34	50	52	71	120	12,500
340	410	423	586	976	102,500
3,400	4,100	4,227	5,857	9,762	1.02×10^6

Table C.4. Illuminance Levels At Operational Depths in Ocean and Harbor Waters for Two Conditions of Surface Illuminance (ft. candles)

Type of Water	Depth (m)	Surface Illuminance (ft. candles)	
		Direct Sunlight 10^4	Overcast Day 10^2
Coastal Ocean	5	2.0×10^3	2.0×10^1
	10	4.4×10^2	4.4
	20	2.6×10^1	2.6×10^{-1}
Harbor	5	2.1×10^2	2.1
	10	5.9	5.9×10^{-2}

D. Peripheral Location

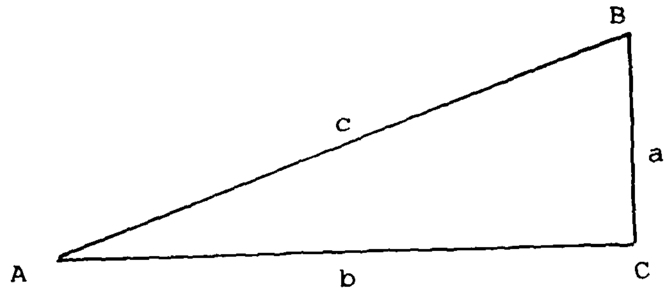
1. Problem Analysis

In vehicle system applications, it is often the case that the operator's visual attention is demanded almost continuously by one critical display function: e.g., the heading error display in submersibles. This display is located in the center of the operator's console in direct line of sight. Other, less critical information is displayed in peripheral areas of the console, and the operator develops a visual scanning pattern to update his information about these other aspects of system status or mission progress. The designer's problem is to decide where on the console to place these secondary information displays relative to the centrally-located primary display.

The shape of the useful visual periphery in underwater system applications is different from air environments due to exaggerated bending of light rays in the periphery caused by the change in velocity of light through water vs air which occurs at the diver's faceplate.

2. Translation Aids

Research results about the usefulness of peripheral visual fields for one kind of visual task or another are typically reported in peripheral angle or off-axis angle or eccentric angle. Basically, the angle referred to is the angle at A in the diagram to follow:



where as elements in the peripheral display application:

_A_ is the location of the diver's eyes.

_B_ is the location of the peripheral display element.

_C_ is the center of the console.

_a_ is the distance by which the peripheral display at _B_ is offset from the center console display at C.

_b_ is the direct, line of sight, zero eccentricity distance from the diver's eyes to the center of the console.

_c_ is the distance traveled by light from the peripherally located display to the diver's eyes.

The geometry of the peripheral display problem has three potential uses to the display designer in interpreting research reults about peripheral visual fields and analyzing the problem of locating peripheral displays.

a. A recommendation is expressed as a peripheral angle, off-axis angle, or eccentric angle and the designer wants to translate this angle at the eye to a linear distance on the face of the console. The applicable trigonometric function for this problem is as follows:

$$a = (\text{Tan } A)(b)$$

b. The designer is considering a given linear displacement from the center of the console as a potential solution to a display location problem and wants to

know the peripheral angle of that location. The applicable trigonometric function for this problem is as follows:

$$\text{Tan } A = \frac{a}{b}$$

c. The designer wants to know the length of the light path from a peripheral location on the console to the diver's eyes. The designer will need this value to calculate required luminance of the peripherally located light. The applicable trigonometric function for this problem is as follows:

$$c = \frac{a}{\text{Sin } A}$$

Table D.1 is a guide to translating eccentric angles and console distances into distance from the center of a console and distance to the eye of a peripherally located display.

Table D.1. Distance (Inches) from Console Center (a) and Distance to the Eye (c) for Various Eccentric Angles (A) and Eye-to-Console Distances (b)

Eccentric Angle At A	b = 10"		b = 14"		b = 18"	
	a	c	a	c	a	c
5°	.9	10.3	1.2	14.0	1.6	18.4
10°	1.8	10.4	2.5	14.4	3.2	18.4
15°	2.7	10.4	3.8	14.7	4.8	18.5
20°	3.6	10.5	5.1	14.9	6.5	19.0
25°	4.7	11.1	6.5	15.4	8.4	19.9
30°	5.8	11.6	8.1	16.2	10.4	20.8
35°	7.0	12.2	9.8	17.1	12.6	22.0
40°	8.4	13.1	11.8	18.4	15.1	23.5
45°	10.0	14.1	14.0	19.8	18.0	25.5
50°	12.0	15.7	16.7	21.8	21.5	28.1

3. Recommendations

Limits to the placement of display elements into the peripheral visual field depend on the visual task. For example, if the operator need only detect the onset of a signal light, the light element can be located farther into the periphery than if he needs to read a word or a number.

- If the display is a signal to be detected

  Detection of peripheral signals is reliable and fast to a limit of 47^{o} eccentric angle when the signal light is in the blue/green to green color range. At an eye-to-console distance of 14 inches, 47^{o} eccentric angle is 15 inches from the center of the console. Display color is an important determinant of peripheral detection; blue/green and green light scatters and the diver detects a 'bloom' of light in the water. If non-scattering, red light were substituted for green in the previous example, the peripheral limit would be 9 rather than 15 inches of lateral displacement from the center of the console. Figure D.1 (p. 22) illustrates the limits to peripheral location for signal detection.

- If the display is numbers or letters to be read

  An operator attending to a centrally located display can accurately read peripherally placed words or numbers to a limit of 33^{o} eccentric angle. At an eye-to-console distance of 14 inches, this angle translates to 9 inches of lateral displacement from the console center. Display color does not affect this recommendation; red numbers are as accurately read as green numbers at 33^{o} eccentric angle. Figure D.2 (p. 23) illustrates the limits to peripheral location of alphanumeric displays for accurate reading.

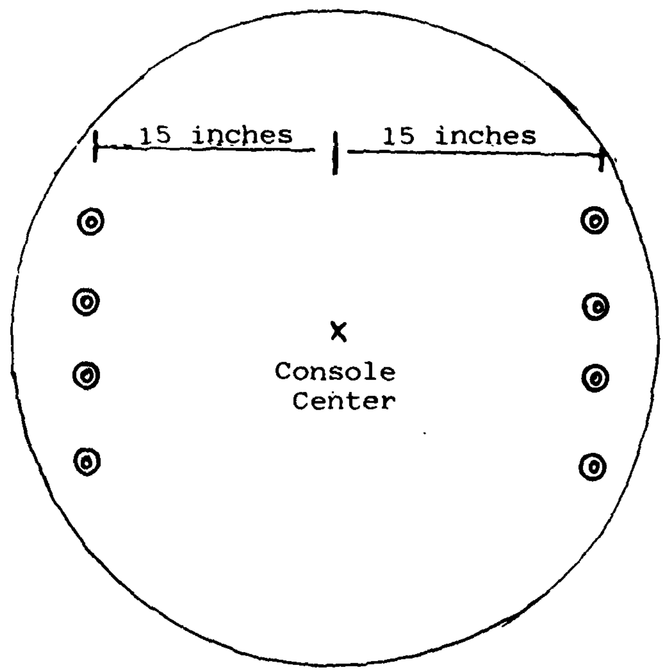


Figure D.1. Detecting Peripheral Signals

Peripheral limits for fast, reliable detection of warning or alert-signals while the operator is attending to a central display. Signal lamps must be blue/green or green (500-540 nm) and of a luminance adequate for the turbidity condition, lamp size, and viewing distance.

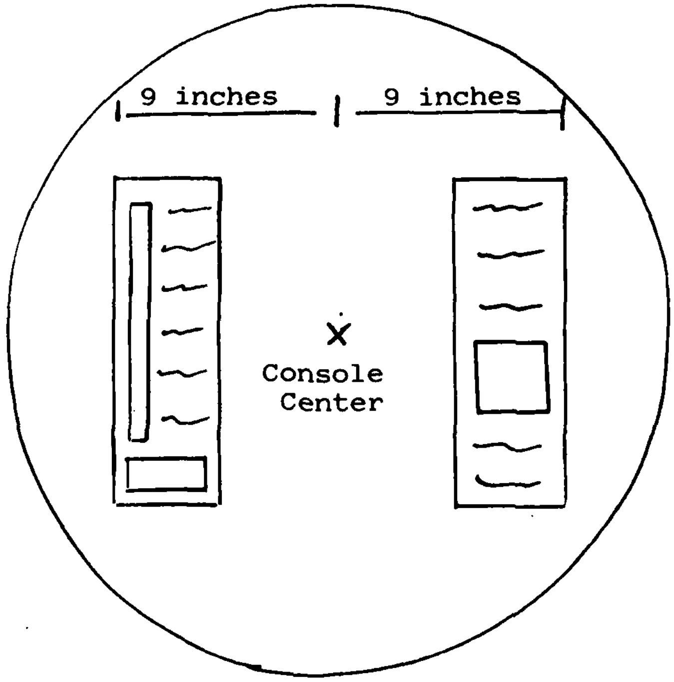


Figure D.2. Reading Alphanumeric Displays in the Periphery

Peripheral limits for >96% accuracy in reading numbers, letters, words and other symbols while operator is attending primarily to a central display. The visual scanning pattern requires eye movement only. Given adequate display luminance, color is not a factor in this visual task.

E. Use of Color

1. Problem Analysis

Wavelength is the physical characteristic of light which determines the perception of color, and the use of color in underwater display applications is a more complex problem than it is in air. This is because air transmits all wavelengths equally well, while water is wavelength selective. Clear water absorbs energy as an inverse function of wavelength (longer wavelengths, reds, are absorbed over a much shorter path length of water than the shorter, blues, wavelengths). Also, very small particles suspended in the water scatter light energy selectively by wavelength (short wavelength energy is reduced by scattering to a greater extent than is long wavelength energy). Consequently, any natural body of water will be maximally transmissive to a single wavelength depending on its particular turbidity characteristics. As light is transmitted through a natural body of water, its original spectral composition is progressively narrowed toward that wavelength to which the water is maximally transmissive. For example, sunlight penetrating the surface of the water tends toward blue-green in the open oceans, toward green in coastal ocean waters and toward red in highly turbid inshore waters.

These physical phenomena have important implications for display design. One is that display color can be chosen to match the wavelength transmission characteristics of the operational water. Another consideration is that ambient light in the water will tend to be monochromatic, and since the human visual-perceptual system adapts to monochromatic light, the color appearance of colored displays will vary according to the color of the ambient water.

2. Translation Aids

Manufacturers' catalogues usually describe colored displays by both color name and peak wavelength. Although wavelength is usually reported in nanometers (nm), nanometer equivalents include millimicron (mμ) and 10^{-9}m. The in-air color appearance of light at different wavelengths is shown in the following figure.

Wavelength (nanometers)	Color Name
460	
	Blue
480	
	Blue-Green
500	
	Green
520	
540	
	Green-Yellow
560	Yellow-Green
580	Yellow
	Yellow-Orange
600	
	Orange
620	Red-Yellow
640	Red

Figure E.1. Color Names Associated with Wavelengths

3. Recommendations

a. Color As An Aid to Search and Detection of Painted Objects

- The most visible color of paint underwater depends on the spectral composition of the illuminating light. With natural illumination, i.e., sunlight penetrating from the surface, use blue-green paint in clear ocean water, green or yellow paint in coastal water, and orange or red paint in very turbid inshore water for maximum visibility. Where an object must be used in various waters, use white paint. White is always among the most visible paints since it reflects whatever wavelengths of light reach it through the water. Fluorescent paints tend to be more visible than regular paint since they convert very short wavelength energy into wavelengths more compatible to human vision.

- When painted objects are to be illuminated artificially, the most visible colors depend on the spectral composition of the artificial illuminant. For example, mercury vapor lamps contain mostly short-wavelength energy and are good illuminants for blue and green paint. Incandescent lamps contain primarily long-wavelength energy, and so are good illuminants for yellow, orange and red paints.

b. Color As An Aid to Legibility of Self-Luminous Displays

- In the majority of applications, the viewing distance will be short and color will not affect legibility; luminance will be the major determinant of legibility. There are exceptions, however. One is the use of red light in highly turbid water; a second is the use of color in illuminated water.

- In dark, highly turbid water environments such as bays, rivers, and harbors, red (640 nm) self-luminous digits or symbols are seen clearly at lower levels of luminance than any other color even at short (10-inch) viewing distances. Also, red light does not scatter in turbid waters providing a measure of covertness which may be a concern in particular military contexts.

- In special applications where self-luminous symbols must be read in relatively shallow water during daylight, i.e., there is high ambient illuminance at the diver's operating depth, colors complementary to the ambient water color will be seen most easily.

The recommended colors for self-luminous or transilluminated symbols, therefore, are also the complements of the recommendations for painted symbols under conditions of high ambient illuminance. Table E.1 presents recommended colors for most legible lights and paints in natural waters illuminated by sunlight.

Table E.1. Most Legible Color of Self-Luminous and Painted Displays in Natural Waters Illuminated by Sunlight

Type of Water	Ambient Water Color in Sunlight	Most Legible Colored Lights for Self-Luminous Displays	Most Legible Colored Paints for Painted Displays
Open Ocean	Blue-Green	Yellow Orange Red	Blue-green
Coastal Ocean	Green	Red	Green
Harbors, Rivers and Bays	Orange-Red	Blue-green Green	Orange Red

c. Color As An Aid to Detection of Peripheral Signals

- If differently colored signal lamps are of equivalent luminance use short wavelength light: blue/green or green in color name, 500-540 in nanometers. Greenish light is scattered by suspended particles creating a bloom of light in the peripheral field that is quickly and reliably detected. This effect occurs even in the relatively clear water of the coastal oceans.

d. Color As A Coding Technique

- Since display luminance is the primary determinant of legibility in underwater environments, the use of color as a coding device should be approached with the following cautions:
  (1) Placing a color filter over a white light source always reduces the source luminance to some extent.
  (2) The amount of luminance reduction is a function of the energy distribution of the source and the color of the filter. Source lamps are typically incandescent tungsten, most of whose energy is in the longer wavelengths; i.e., there is very little 'blue' energy in the source. Since a color filter removes all wavelengths except those of the desired color, placing a blue filter over an incandescent lamp can potentially remove so much of the source luminance as to darken the display below the threshold of legibility.

(3) Since different colored filters reduce the luminance of the source lamp in different amounts, the use of several colors on a display panel will make the colors vary in perceived brightness. What may be intended as color coding may result in brightness coding. A display design objective is to create panel readouts of equivalent brightness, and so different color elements may need to be differentially powered in order to achieve equal luminance through the filter.

- In illuminated waters, the color appearance of colored lights and of colored paints will be modified by the ambient hue in different ways:

(1) The color appearance of painted objects will be modified in the direction of the hue of the ambient light. For example, in coastal ocean waters the ambient light will tend toward green. Therefore, white paint will appear green, red will appear orange, orange will appear yellow, yellow will appear green, green paint will appear very green, and blue paint will appear a blue-green. In a harbor or other highly turbid inshore waterway, the ambient light from sunshine will tend toward red. Therefore, white paint will appear red, red paint will appear very red, orange will appear red, yellow paint will appear orange, green paint yellow, and blue paint, green or purple.

(2) The color appearance of colored lights on the other hand will tend toward the hue of the complement of the ambient light. For example, in coastal ocean waters the ambient light from the sun is filtered

toward green. The human visual-perceptual system quickly adapts, and the ambient light as well as other green lights appear a neutral gray. The complement of green, i.e., red, is then added to the perception of other lights; e.g., white light appears red. Table E.2 (p. 31) shows the commonly experienced color appearances of a range of colored light in dark and illuminated waters.

- The potential for color confusion is so great in systems which must operate in a range of underwater environments, that color coding should be minimized. For reliable discrimination use only two colors: one from either end of the spectrum, i.e., a red and a blue-green.

Table E.2. Color Appearances of Self-Luminous Colored Displays in Different Environments

Display Wavelength (nm)	As Seen in Air	In Dark Water		In Illuminated Water	
		Coastal Ocean	Harbor/Bay	Coastal Ocean	Harbor/Bay
473	BLUE	BLUE	BLUE	BLUE	BLUE
503	GREEN	GREEN-blue	GREEN-blue	BLUE	BLUE
552	GREEN-yellow	GREEN-white	GREEN	WHITE	GREEN
579	YELLOW	YELLOW-white	YELLOW	RED-white	WHITE
608	RED-yellow	RED-white	RED-yellow	RED	RED
640	RED	RED	RED	RED	RED
ALL	WHITE	WHITE-yellow	YELLOW-white	RED-white	BLUE-white

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Kailua, Hawaii 96734

Dr. A. L. Slafkosky
Scientific Advisor
Commandant of the Marine Corps
Code RD-1
Washington, D.C. 20380

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Panama City, Florida 32407

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Human Engineering Consultant
6085 Odessa Avenue
La Mesa, California 92041

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Code U11
Naval Surface Weapons Center
White Oak
Silver Spring, Maryland 20910

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Washington, D.C. 20374

Commanding Officer
Underwater Demolition Team 21
U.S. Naval Amphibious Base
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